TESTING THE BIPOLAR OUTFLOW MODELS: A WELL-SHAPED BIPOLAR OUTFLOW SHELL IN MON R2

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RESUMEN

Wc identify in our $CO\ J = 1-0$ maps an "cgg~dallt-shaped", thin bipolar outflow shell which outlines the extended blue lobe of the massive bipolar outflow in the central region of Mon R2. The projected length and width of the shell are about 5.3 pc and 2.7 pc respectively, and the averaged projected thickness of the shell is ~ 0.3 pc. This remarkably well-defined narrow shell along with the peculiar line profiles strongly favor outflow models with largely unfilled lobes. A good fit of the shape of the shell by the recent simple outflow model of Shu *et al* seems to suggest that the model Ills.y have grasped some essential elements of the real situation, although our consideration of the mass distribution confirms a conclusion of a previous study (Masson & Chernin 1992) that the model predicts too much mass at small polar angles ($< 14°$).

ABSTRACT

We identify in our $CO\ J = 1-O$ maps an "eggplant-shaped", thin bipolar outflow shell which outlines the extended blue lobe of the massive bipolar outflow in the central region of Mon R2. The projected length and width of the shell are about 5.3 pc and 2.7 pc respectively, and the averaged projected thickness of the shell is ~ 0.3 pc. This remarkably well-dcfirlcd narrow shell along with the peculiar]inc profiles strongly favor outflow models with largely unfilled lobes. A good fit of the shape of the shell by the recent simple outflow model of Shu *et al* seems to suggest that the model may have grasped some essential elements of the real situation, although our consideration of the mass distribution confirms a **conclusion)** of a previous study (Masson & Chernin 1992) that the model predicts too much mass at small polar angles (< 140).

Key words: **interstellar: matter ISM: jets and outflows - star: formation stars: mass 10ss stars: pre-mai i-sequence**

1. Introduction

The bipolar outflow phenomenon has been one of the most exciting, and most intensely-studied aspects of star formation (cf. Snell 1987; Shu, Adams & Lizano 1987). However, wc may still be years away from a relatively complete understanding of the phenomenon. In fact, wc cannot yet discriminate among even some very simple phenomelogical outflow models. A few such models include the filled biconical 10Lc model by Cabrit & Bertout (1 986; 1990); the shell model by Moriarty-Schieven & Snell (1 988); the thin paraboloid] shell model by Meyers-Rice & Lada (1991) and, more recently, the model of Shu *et al* (1 991, hereafter S1{.1,1,) and the jet-driven outflow models of Raga & Cabrit (1 993) and Masson & Chernin (1 993). However, it is clear that a central element of these models is the possible existence of molecular shell swept-up by stellar winds.

The Mon R2 bipolar outflow (Bally & Lada 1983) at a distance of 830 pc (Herbst & Racine 1976) is one of the largest in size and in mass among the two hundred or so outflows identified to date (Bally and Lane 199]). Wolf, Lada & Bally (1 990) and Meyers-Rice & Lada (1 991) have presented detailed observational studies of the Mon R2 outflow and suggested possible shell structure based on the shape of line profiles, yet they do not identify limb-brighted shells.

2. Observations

Observations of the $CO\ J=1-0$ transition in Mon R2 were made using the QUARRY 15-element focal plane array at the 14 m FCRAO telescope in New Salem, Massachusetts, in 1991 April through December. The map is centered on the position of an in frared star cluster, $\alpha(1\,950) = 06^h05^m22^s$, $\delta(1\,950) = -06°22'25''$ (cf. Beckwith *et al* 1976). The spacing of the data points is 25" while the FWHM beam size of the telescope is about 45" at 115 GHz (Xie 1992; Xie, Goldsmith & Patel 1993, hereafter XGP).

Onc striking feature in the maps of $^{12}CO\ J=1-0$ emission is the appearance of an "cggl)lant-shaped" shell feature in several velocity channel maps with velocity close to $10.5\, km\, s^{-1}$, the centroid velocity of the core) extending from the (O, O) position to the hTortli-West for about 20 arcmin (Xie 1992; XGP). Figure 1 presents an overlay Of the high velocity gas with the shell seen in the $V_{LSR} = 10.88\, km\ s^{-1}$ CO channel map. The blue-shifted lobe of the bipolar outflow rests nicely within the boundary of the shell, posing the immediate possibility that we arc witnessing the limb-brightened thin shell swept up by the collimated stellar wind from the central driving source of the bipolar outflow.

3. The Outflow Shell

The model of SRLL and the jet-driver] models of Masson & Chernin (1993) and Raga & Cabrit (1 993) deal with a whole, closed outflow shell, while some other models (cf. Moriarty-Schieven & Snell 1988; Meyers-Rice & Lada 1991) have considered shells with open ends. The observed outflow shell in Mon R2 is surely in favor of models with closed ends.

The SRLL model is particularly impressive in its simplicity and beauty in terms of mathematical construction of the physical problem, which allows a relativel y easy comparsion of observations with the model predictions. In a spherical polar coordinate system (r, θ, ϕ), both the stellar wind and the ambient surrounding medium arc assumed to have axial symmetry and reflection symmetry about the equatorial plane $(\theta = \pi/2)$. The ram pressure force per steradian, $f(\mu)[g\ cm\ s^{-2}\ sr^{-1}]$, of the wind is a function only of $\mu(= cos\theta)$

$$f(\mu) \propto P(\mu), \tag{1}$$

and the density of the ambient material $\rho(r,\mu)[g\ \ cm^{-3}\ sr^{-1}]$ can be expressed as

$$\rho(r,\mu) \propto \frac{Q(\mu)}{r^2}, \tag{2}$$

where $P(\mu)$ and $Q(\mu)$ arc dimensionless functions not specified by S1{,1.1.. One approach is to let $P(\mu)$ and $Q(\mu)$ have power-law form (Masson & Chernin 1992), $P(\mu) \propto \mu^{\alpha}$ and $Q(\mu) \propto \mu^{-\beta}$. With these simplifications and the further assumption that the stellar winds move out by sweeping the ambient medium into a thin shell with momentum conservation ("snowplow") and that the net mass flow along the O direction in the thin shell is negligible, the shell velocity $v_s(\mu)$ along each radial direction $(\theta = constant)$ will be

$$V^*(\mu) = v_0 \mu^{\delta}, \tag{3}$$

where $\delta = (\alpha + \beta)/2$ and V. is the shell velocity in the polar direction. Since $v_s(\mu)$ is independent of time, the shell will develop self-sirnilarly, $r_s(\mu) = v_s(\mu)t$.

The emission from the swept-up gas in the shell is expected to show limb-brightening in some velocity channel maps, as can be easily demonstrated by deriving the locus of constant-velocity emission from the swept- up gas.

Now how do wc compare the shape of the observed shell with the prediction of the model ? The simple way that XGP has taken is to parameterize 4 observable quantities of the outflow shell in 4 parameters of the model, such as δ, V_0, inclination angle i and outflow age t, and then to determine the model parameters. The 4 observable quantities include the maximum width, length of the shell, the maximum Muc-shifted velocity along the line of sight and the projected displacement of the position where the blue-shifted velocity maximizes. We find $v_0 = 15\ km/s$, $\delta = 6$, $i = 70°$ and $t = 3.5 \times 10^5 years$. This inclination angle is consistent with the 66° determined by Meyers-Rice & Lada (1 991). Figure 2 presents an overlay of the modeled constant velocity locus with the velocity channel map at 10.8 km/s. We scc that the SRLL model provides a remarkable fit to the shape of the observed outflow shell.

4. Discussion

Besides the shape of the shell, another aspect of the model is the mass distribution in the shell, which depends on α and β respectively. Maroon & Chernin (1 992) investigated this aspect by studying the predicted line profile averaged over the whole outflow, and concluded that the SRLL model predicts too much mass at small polar angles. XG P presented a different approach. They parameterized the column density sampled by the telescope beam as a function of the centroid velocity of the blue-shifted shell along the outflow axis. If the ^{12}CO crnission from the shell is assumed to be optically-thin, then this function corresponds to the integrated intensity of ^{12}CO as a function of the shell velocity along the outflow axis. XGP found that while the SRLL model in its present form dots lead to far more mass at very small angles than observed, it seems to provide satisfactory explanations to the mass distribution as a functiòn of velocity over a large range of polar angles. Being encouraged by this and the remarkable fit to the shape of the outflow shell, XGP argue that the SRLL model may have grasped the essential physics of the phenomenon and the discrepancy at very small polar angles between the model and the data may be due to possible complications such as inhomegeneity, clumpiness etc., which arc not properly characterized by the over-sirl)p]ificd model at present.

One thing worth mentioning is that we have only treated the blue-shifted lobe so far. The outflow actually has considerable structure and complications (Meyers-Rice & Lada 1991; Xic 1992; XGP). Two of these complications seen in Figure 1 are the "bending" of the red-shifted lobe and the serious overlapping of red- and blue-s}liftcd high velocity gas c1osc to the outflow center whit.b is not expected for the estimated inclination angle of $\sim$ 70°. Xic (1992) suggests that most of these can be understood in that the central core and the bipolar outflow arc located on a large expanding molecular shell which now dominates the overall giant molecular cloud and triggered new generations of star formation (Xic & Goldsmith 1993). M'hilt the blue lobe of the outflow is developing into the relatively homogeneous medium which has not yet been swept-up by the large scale expansion, the red lobe is developing towards the cavity which is largely cleared out of molecular material and the red lobe is "squashed" so that it is forced to develop sideways.

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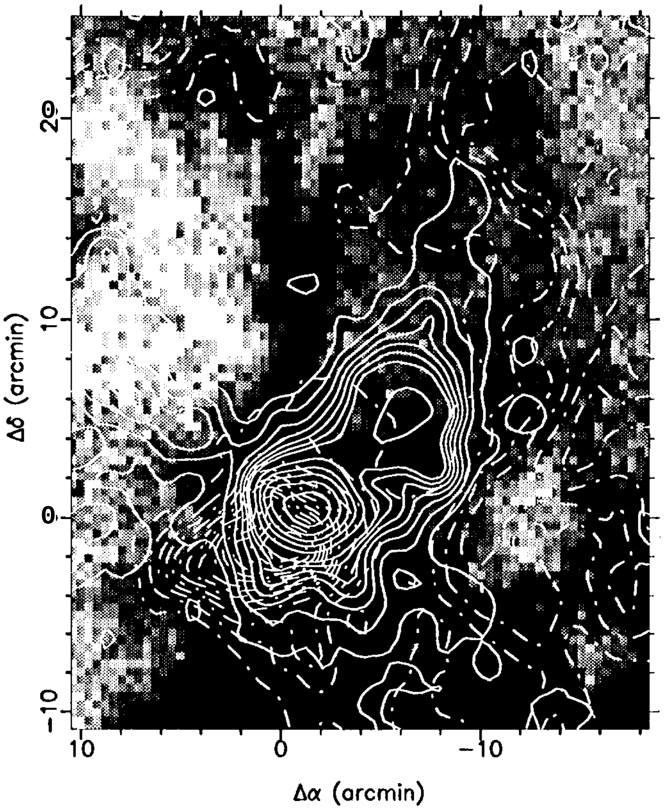

Fig. 1.- An overlay of the shell feature (grey scale) with the high velocity gas (contours). Solid contours are for the blue-shifted emission (V_{LSR} = 2– 8 $km\,s^{-1}$) with levels 1, 2, ... 7, 10, 13, ... 22 K $km\,s^{-1}$. The dashed contours are for the red-shifted emission ($V_{LSR} = 12 - 18\,km\,s^{-1}$) with levels 2, 4, ... 26 K km s-1. The grey scale ranges from 1 K (white) to 14 K (black).

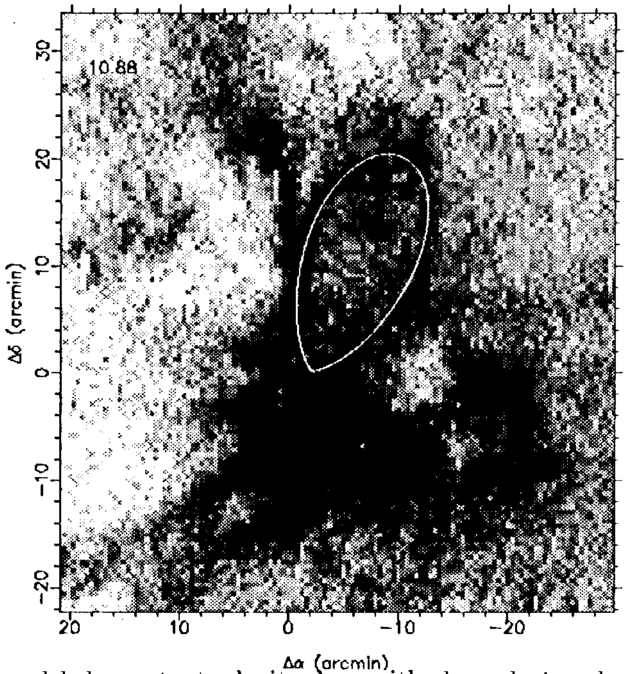

Fig. 2.- An overlay of the modeled constant velocity locus with the velocity channel map at 10.8 km/s. The grey scale ranges from 1 K (white) to 14 K (black).